INTERNAL STRUCTURES OF IGNEOUS ROCKS; THEIR SIGNIFICANCE AND ORIGIN; WITH SPECIAL REFERENCE TO THE DULUTH GABBRO[1]

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INTRODUCTION

It is commonly said that igneous rocks are structureless, or of massive structure, as distinct from stratified or banded rocks of other origin. When considered in detail, however, they are known to show a number of characteristic structures. Under special conditions igneous rocks develop lithophysae, orbicules, bunchy segregations, spherulites, etc. But besides these there are a number of rock masses which show a banded structure. It is this banding which is the main subject of this paper, first as to its relation to the form of the rock mass, and later as to its origin.

Three somewhat distinguishable features give a plane structure to an igneous rock unaffected by metamorphism; they will be discussed here as banding, sheeting, and fluxion structure. Various geologists have noted these structures and combinations of them under the terms bedded, stratiform, gneissic, laminated, foliated, trachytoid, schistose, linear, streaked, platy, schlieren, layers, benches, etc.

Banding.—The banding noted in many igneous rocks is an alternation of mineralogically unlike layers or flat lenses (Figs. 1, 2, 3, and 4). The dip and strike of the bands can be estimated in many cases, but may show minor undulations and bunches. In some cases the layers are all thin, but in others they range more widely, up to a hundred feet. The line of division between bands may be sharp or gradual. The texture of one band is in most cases very little different from the textures of adjacent bands, and the

[1] Published by permission of the directors of the United States Geological Survey and the Minnesota Geological Survey. Appeared first as part of a thesis presented at Yale University.

minerals interlock across the contact. In most cases there is no great difference in the mineral constituents of the bands, but only

FIG. 1.—The banded gabbro of Duluth, Minnesota. The banding in this outcrop is about as conspicuous as in the average.

FIG. 2.—The bands in this gabbro outcrop are irregular and the color contrast is very slight, but the lighter bands are polished by glaciation.

in the relative abundance of the minerals. The colors of adjacent bands may be only slightly different, or in some cases may show a strong contrast. In a rock mass containing a variety of minerals

any one mineral may be quite completely segregated in certain bands. Where the minerals of any band weather more rapidly

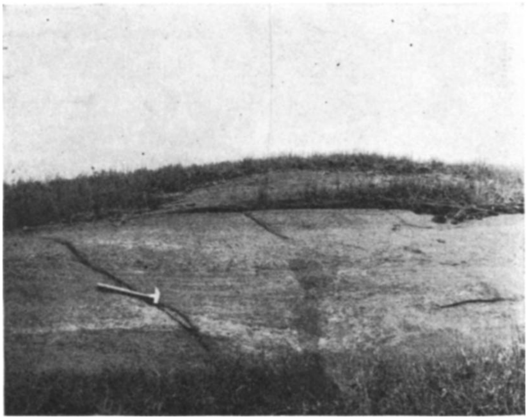

Fig. 3.—Faint banding in the Duluth gabbro. These bands curve slightly, and a white band near the hammer divides to the left.

Fig. 4.—Conspicuous bands of peridotite and gabbro near the base of the Duluth gabbro.

than those of adjacent bands, such bands appear as grooves in the surface. The composition of the bands is independent of the composition of the wall rocks. There are no transverse dikes or connections between bands.

A classic example of banding is that in the gabbro mass of the Isle of Skye (1, 2).[1] There are many parallel layers of lighter and darker material, and some of the bands curve conspicuously. Another prominent case is that on Ornö (3) just south of Stockholm, where the alternate bands are black and white, and the banded rock is said to constitute the periphery of an intrusion. An equally notable color banding appears in the large igneous Ilimausak rock in Greenland (4). The bands are from one to three meters thick, and three main rock types alternate with remarkable regularity. The bands are saucer shaped in a large way and there are no apophyses between bands. Transition zones are narrow and the texture is unchanged at the contacts.

The Laurentian gneisses have a banding that is in some places clearly an original igneous structure (5). Some bands pinch out, and all are notably different from the roof in composition. There are no sharp contacts and no transverse dikes, though some related pegmatites cut across the bands. Many papers on Canadian igneous rocks mention structures of this sort (6, 7, 8). The banded rocks studied under the microscope show in the most positive manner that the structure developed while the rock was still molten, or at most only partly crystalline. There are in many specimens no traces of mineral deformation; nor is there any reason to suppose that recrystallization has obscured the signs of some previous deformation. Mount Johnson, near Montreal (9), shows bands rich in feldspathic material alternating with others richer in iron and magnesian constituents. The dip and strike can be measured. The alkali syenites of eastern Ontario (10) show bands. The Sudbury norite is reported by Mr. Hugh Roberts, of Minneapolis, on the basis of recent exploration, to show an alternation of mineralogically differing bands.

The Cortlandt series in New York has an "original gneissoid" structure in which the bands differ in mineral composition. While there are sharp contacts, it is characteristic that the grains in all cases interlock across the contact. None of the series exhibits any great amount of shearing (11). In the Adirondacks, bands one to one hundred feet thick show alternating gray and pink colors (12).

[1] Numbers refer to entries in the bibliography at the end of the paper.

In Maine some gabbro masses show alternating bands about two inches thick, in some of which segregation of feldspar produces light colors (13).

The rocks of Lizard show a linear structure and an occasional distinct banding which is said to have nothing to do with dynamometamorphism (14). Such banded rocks are reported from the Himalayas (15), the Kola Peninsula (16), and the British Isles (17, 18). In the "Cottian sequence" (19) the banding has been supposed to be metamorphic, but there are some dikes with a foliation parallel to their walls and at a high angle to the structure of the schist.

FIG. 5.—Apophyses of feldspathic Duluth gabbro into its traprock roof, east of Duluth Heights.

The banding of the Duluth gabbro was long ago mentioned (20, 21), but new work has recently been done on the area by the geologists of the Minnesota Geological Survey. The structure is exposed in typical, as well as in some exceptional, conditions at the city of Duluth. The gabbro intrusion (Fig. 5) occurred after the accumulation of a great thickness of diabase and other flows of the Keweenawan. It spread at or near the base of the flows, and along the unconformity at the base of the Keweenawan sediments a little below the flows. While the roof and floor are not an exactly continuous horizon, the transgression of a few hundred feet in a mass

a hundred miles long is insignificant. The relations are well exposed in the western part of Duluth. By detailed study it is found that the intrusion of gabbro occurred at two or more times, for at Lincoln Park and elsewhere the chilled contact and apophyses of one show that an older gabbro had already cooled. Banding (Fig. 1) is shown chiefly by the later mass, which is much the larger of the two.

In some places two rock types alternate, but in most there are several minor rock varieties in irregular alternation. The bands vary in thickness from a fraction of an inch to many feet. It is likely that in the average the gabbro does not show such minute or intimate lamination as some associated sediments,[1] but while there may be a general difference, each varies to resemble the other. Some contacts between adjacent bands are abrupt, but more commonly there is a complete gradation between them. Some neighboring bands contrast strongly in color, while others are visible only on careful scrutiny; some are intensified by weathering, producing black, brown, gray, and white colors; some are conspicuous only from a difference in the degree of glacial polish (Fig. 2). Some large outcrops at Duluth show faint bands as much as fifty feet wide. It is therefore evident that smaller outcrops a few feet wide may not reveal a banded structure even if it really exists. The whole area has been mapped as banded, because the outcrops which did not show the structure were small and not numerous; they may represent other variations of the mass, but are here considered as probably thick bands. Most of the bands are regular, parallel, and fairly continuous along the strike and dip. However, there are locally lenticular bands, and spots or bunches along the bands, as shown in Fig. 2. Rarely the bands curve and finger out into each other (Fig. 3) and are as complex in structure as the ancient metamorphic gneisses. This irregularity is not as prominent as in the gabbro of the Isle of Skye (1); but locally the average dip of about 25° to the east increases to 80° with some variation also in strike. Although these outcrops may resemble metamorphic gneisses enough to be deceptive, a thorough study of

[1] U. S. Grant, "Contact Metamorphism of a Basic Igneous Rock," *Bull. Geol. Soc. Amer.*, XI (1900), 508.

the rocks shows little trace of any crushing or recrystallization. Poikilitic and ophitic structures remain unaffected, and the minerals are fresh. The associated earlier flows and sediments show no such structure as would have developed if the gabbro had been metamorphosed. The structure is therefore a primary one.

In general, the minerals of one band are the same as those of adjacent bands, and the banding is a consequence of difference in proportions of minerals. Textural changes are slight. Rock types at Duluth range from peridotite to anorthosite as extremes, with magnetite gabbro and troctolite as other variations from normal gabbro. A few measurements were made on thin sections of bands of gabbro, and some have been selected and presented in Table I to show how the bands vary.

TABLE I

	Percentages by Weight				
	Plagioclase	Pyroxene	Olivine	Magnetite	Miscellaneous
Common bands	75	10	10	4	1
	65	19	10	5	1
	70	18	0	12	0
Two adjacent bands such as alternate many times	84	12	3	1	0
	62	15	12	11	0
Bands of extreme composition	96	3	0	1	0
	20	44	0	36	0
	49	48	0	3	0
	2	15	70	13	0
	75	2	22	1	0

Detailed observations of the dip and strike of gabbro structure at Duluth show only minor irregularities. Fig. 6 shows the general structure of the gabbro in those townships where observations have been made. It gives the impression of concordance with neighboring contacts. Magnetic mapping of the portion of the gabbro far to the northeast shows the general parallelism of bands and contacts, as well as the probably lenticular nature of the bands, which in Fig. 7 represent titaniferous magnetite ore.

It may be added that some large sills, more or less related to the gabbro (22) and typically exposed at Beaver Bay, on Lake

Superior, show an exactly similar banding. The same gabbro in Wisconsin shows what has been described as a "bedded" structure (23).

There are a number of smaller masses which also show a banding, possibly of similar origin. The Purcell sills gabbro has certain streaks of lighter color (24) in addition to the separation into differentiated zones. A gabbro dike near Boulder, Colorado, has bands of iron ore parallel to the walls (25). A dike in the Isle of Man is similarly banded (26). The Mt. Holmes bysmalith has a color banding parallel to the walls (27). Other examples will no

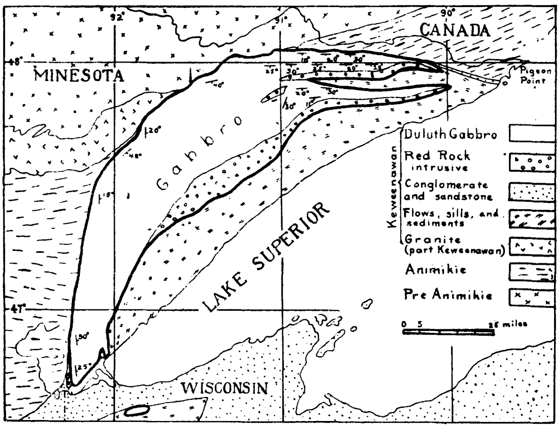

FIG. 6.—Sketch of the area of the Duluth gabbro showing the dip and strike of its internal structure.

doubt be recalled by those who have worked in igneous rocks. A color banding is visible in many flows, but the difference in mineral content of the bands is not always clear.

Fluxion structure.—Certain igneous rocks have an abundance of platy or needle-like minerals, notably the feldspars and hornblende. Many gabbros and syenites show a certain amount of parallelism of such grains (Fig. 8). Most of these rocks show banding of the sort just discussed. The rocks of Lizard (14) and the Adirondacks (12) and Laurentia (5) are "foliated." The Ilimausak (4) rock has "primary schistose structure." The Mt. Johnson rocks (9) have a "fluidal arrangement of grain." The

Ontario syenites have an "original foliated or schistose structure" (10). All of these are noted by the authors as a feature in addition to banding.

The occurrence at Duluth is a particularly good example of this structural feature as well as of the banding. Both the early, relatively thin feldspathic gabbro and the later banded gabbro show a parallelism of plagioclase grains in many outcrops. The smaller sills referred to also show the fluxion structure.

Sheet structure.—When independent of surface changes of temperature, this is probably related to some such feature as the banding and fluxion structure just described, even when they of

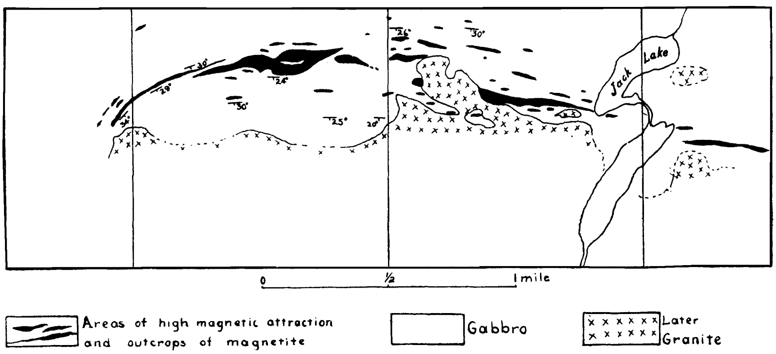

FIG. 7.—Map of three square miles in Cook County, Minnesota, showing in black the lenticular form of the outcrops of bands in the banded Duluth gabbro. In this case the bands carefully mapped are those rich in titaniferous magnetite.

themselves may be inconspicuous. Platy parting is recorded in the Ilimausak rocks (4) and the laccoliths of Highwood Mountains (28) and at Tripyramid Mountain (29) and elsewhere. The Duluth gabbro shows such joints in many outcrops (Fig. 9).

Combinations.—It is evident from the foregoing notes that several masses show two or three structural features at the same time. This is true for a single outcrop as well as for the mass as a whole.[1]

[1] The term "gneiss" may be extended to cover such rocks as these showing banding and fluxion structure, but when this is done the name should be qualified as "primary gneiss." The usage is discussed by Barlow, "Nipissing and Temiskaming Region," *Geol. Survey of Canada, Ann. Rept.*, X (1897), Part I, p. 49; and Miller, *Bull. Geol. Soc.*

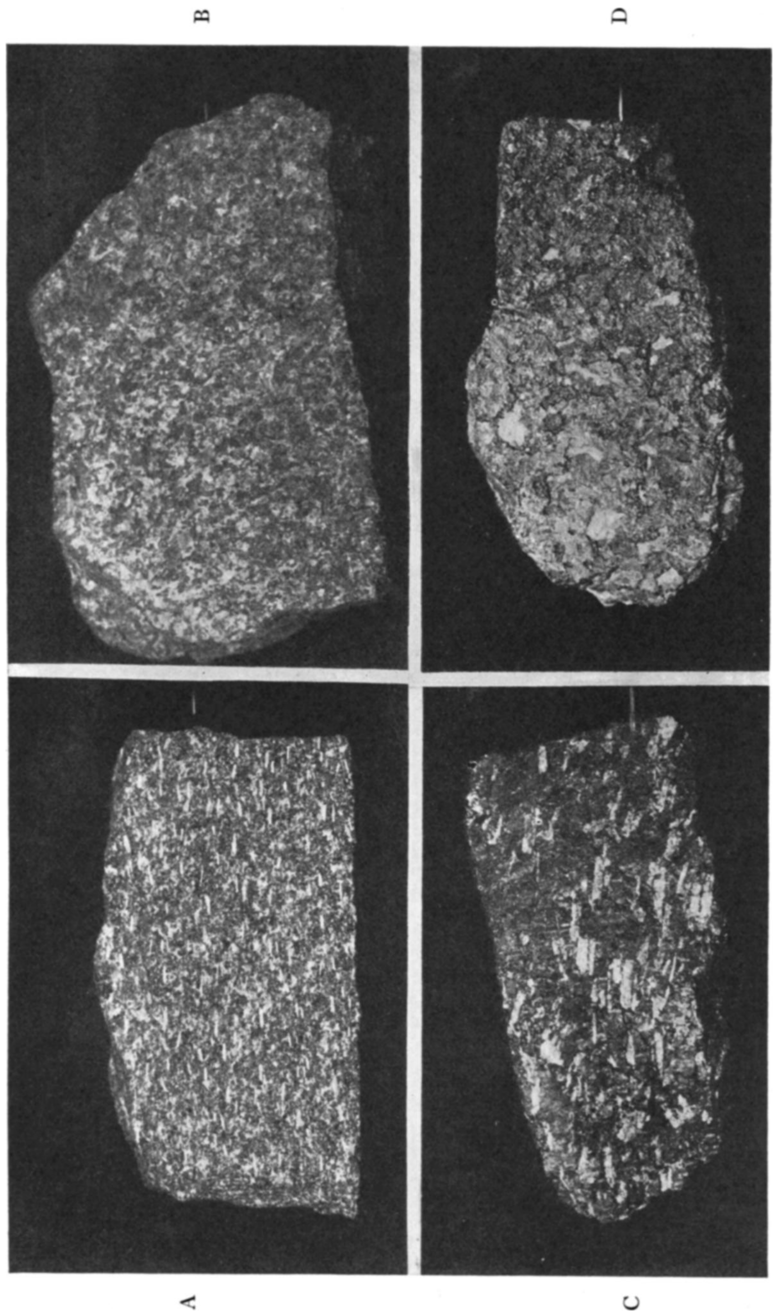

FIG. 8.—Top and side views of gabbro and a magnetite segregation in the gabbro, showing fluxion structure. About one-half natural size.

THE RELATION OF IGNEOUS STRUCTURES TO THE FORMS OF IGNEOUS MASSES

Pirsson finds the parallel arrangement of crystals and the platy parting of the laccoliths of the Highwood Mountains parallel to the roof (28), and has some evidence of a similar relation at Tripyramid Mountain (29). Iddings reports the parting and color banding of the Mt. Holmes "bysmalith" (27) parallel to the walls.

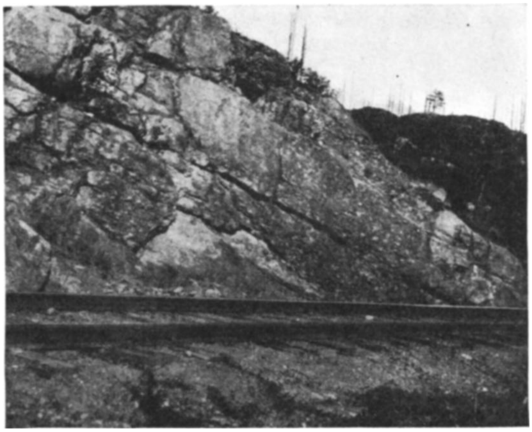

FIG. 9.—Sheeted structure in the Duluth gabbro evidently independent of the surface. Spheroidal weathering also appears.

Rogers finds that the bands in the Cortlandt gneiss bear no definite relations to the borders of the magma (11). However, banding in the Adirondacks is of several kinds, and Miller records "a foliation that boxes the compass around the borders of the stocks" (30). The banding in lava flows and their trachytic structures is often recorded as parallel to the general plane of the flow. Examples

Amer., XXVIII, 455. "Fluidal gneiss" and "injection gneiss," as terms recently developed in structural geology, are probably best restricted to another type of structure. It is detected in tracing igneous injections in bands between masses of a schist of other cleaved rock, or even curving in and out among rock fragments. This results in an alternation of the original cleaved rock (of whatever origin) and the igneous rock. Solution of the original rock and its metamorphism by the magma may produce such an intimate intergrowth as to make distinctions between intrusive and intimate intergrowth as to make distinctions between intrusive and intruded rocks difficult. See Leith, *Structural Geology*, p. 85; and Cross, *Science*, XXIX, 946.

are seen in the Yellowstone banded obsidians (27) and the flows of the eastern (31) and southwestern states (32). The bands in the Purcell sills "approximate a position parallel to the upper and lower contacts of the sill" (24). Barlow records that the strike of the banding is uniform over large areas in the Nipissing and Temiskaming regions, and shows a "marked correspondence in direction with the line of outcrop of the neighboring stratified Huronian rocks" (8). Adams finds the banding of Mount Johnson vertical and clearly parallel to the walls of a volcanic plug curving around the mountain (9). Adams and Barlow say that the strike of the banding and foliation of the alkali syenites of eastern Ontario conforms to that of the adjacent country rock (10). Ussing considers the strata of the Ilimausak mass the upper layers of a batholith, but records that near the walls of the chamber the bands, which are nearly horizontal most of the way, turn up and become parallel to the walls (4). Gregory mentions some dikes which are foliated parallel to the walls, but not parallel to the foliation of the neighboring schists (19). Banding also appears in a dike in the Isle of Man, parallel to its walls (26). Harker says that the banding of the gabbro at Carrock Fell is parallel to "the lie of the intrusion as a whole" with only minor undulations (17). At the Isle of Skye the banding is undoubtedly related to the boundaries. Iddings says that it is "not locally referable to the form or boundary of the body of a particular igneous rock,"[1] but he cannot have seen as much of the structure as Geikie and Teall, who say that each sheet of gabbro "consists of many parallel layers . . . . which correspond in direction with the trend of the sheet itself"(1); or as Harker, who says that the bands dip with the mass as a whole and are in general parallel with the upper and lower surfaces of the sheets (2).

A similar disagreement may be recorded in the case of the Duluth gabbro, where Elftman says that the banding is irregular (21), and more recent data show only minor variations from the direction of the contacts. The agreement of strike with the boundaries of the mass is shown in Fig. 6. The agreement in vertical section is more difficult to prove, on account of the scarcity of exposures showing such vertical sections. A single outcrop at

[1] J. P. Iddings, *Igneous Rocks*, I, 252.

Duluth (in the NW. Cor. Sec. 22, T. 50. N., R. 14 W.) reveals the upper contact of the gabbro with a clear exposure of dip. The roof here dips east a trifle irregularly at an angle of about 15°. At Lincoln Park it may be seen further that the later banded gabbro dips east under the earlier feldspathic gabbro. At the base of the gabbro, where one might search for the exposures of the floor, the relations are confused by pegmatitic and aplitic emanations and differentiates of great variety. At the Paulson mine in Cook County the floor apparently consists of eroded iron formation. Though the dip of the contact is not well exposed, drilling was conducted on the assumption that the bedding of the sediment and the banding of the gabbro indicated the direction of the contact. As far as exploration went, this proved to be true.[1] A floor under the gabbro, conforming to the position of the banding, is also indicated by the constancy of the horizon of the gabbro intrusion, and by the arrangement of differentiates; some heavy segregations are on the northwest, as if a floor dipped under them on that side.

A review of literature and suggestions to be presented later with regard to the origin of these structures has no reference to any process which would tend to develop a banding independent of the boundaries. The favored theories involve movement during crystallization, and it would be expected that such movement would be more or less controlled by the boundaries of the magma chamber.

These results are sufficiently uniform—only one apparent exception—to warrant the assumption that in a large way the fluxion and banded structures, as well as sheet jointing (when not referable to surface weathering), may be a guide to the position of the boundaries of igneous masses, and therefore of great value in mapping igneous forms and interpreting their position. The occurrences include flows, dikes, sills, a plug, a bysmalith, and laccoliths. Exceptions may be found, but even if the idea proves untrustworthy it is worth stating for the sake of stimulating accurate observations and records, which are at present not very numerous.

[1] E. C. Harder, personal communication.

THE ORIGIN OF IGNEOUS BANDING

Former suggestions.—The field study of the structure of the Duluth gabbro led the writer to assume a process of convection during crystallization as its cause. On reference to the literature, it was found that Bowen recently eliminated convection from the list of magmatic phenomena which he considered important (33). No clear statement of the relation between convection and structure could be found, and a review of the various explanations of the banded structure was thought desirable. In addition to suggestions made in connection with specific areas already mentioned, there are some discussions of the phenomena in general papers (7, 33) and textbooks (34).

Banding is so characteristic of metamorphic gneisses that the structure is not rarely referred to secondary processes, but the papers cited above show very conclusively that much of it is primary. Furthermore, as igneous rocks they cannot have been fused in place and retained traces of earlier structure, for the gabbro at Duluth and banded rocks in a number of other places are known to be intrusive into both their roof and floor (Fig. 5), neither of which is much metamorphosed. Of the other possible causes of banding, the following tabulation includes the chief suggestions found:

1. Partial assimilation of inclusions, forming schlieren
2. Lit par lit, or fluidal gneiss
3. Deformation during solidification
4. Deformation just after solidification
5. Streaked differentiation, with reference to rhythmic cooling or intrusive action
6. Successive intrusions:
   a) Cooling separately and successively
   b) Cooling later, all together
7. Heterogeneous intrusion

The writer would add:

8. Convection during crystallization differentiation

Discussion.—The idea of partial assimilation of xenoliths, or lit par lit injection of wall rock as an explanation of banding, loses

its main support when it develops (as in Duluth) that the floor and roof are rocks of about the same composition as the average gabbro, and that the bands range from anorthosite to peridotite—with compositions that could hardly be synthesized from any rocks in the region. It is admitted that schlieren, developed from xenoliths, occur in some local spots, but they have no relation to the banding and show no extreme in composition.

Deformation during crystallization might explain the orientation of grains, but cannot clearly explain the banding.

The process of differentiation has not been described so as to explain the banding. It is, of course, probable that a rhythmic variation in the process of crystallization would give a rhythmic alternation of rock deposited, but that furnishes no explanation of the fluxion structure. None of the theories of differentiation outline a process that will result in a combination of gravitative arrangement, parallel banding, and parallelism of grain.

It is well said that the necessary conditions for igneous banding are heterogeneous composition and differential movement (34). Of the suggestions listed above, those which fulfil these two conditions are successive intrusion, heterogeneous intrusion, and deformation during crystallization. It is to be noted that each of these involves movement. The orientation of the platelike grains can hardly be accomplished except by some sort of movement of the magma while the plates are suspended in it. Such orientation is seen in surface flows where it is parallel to the direction of flow, and is often visible in thin sections of trachytes. To be sure, the settling of crystals, which idea is in special favor recently, might be thought of as analogous to the settling of mica plates in a sediment. Those falling on a flat bottom might adjust themselves in horizontal and parallel positions. On the contrary, it does not seem probable that such an orientation would occur in a crystallizing magma. The settling is slow, so that other crystals might lodge close to the plate and prevent its rotation. Furthermore, the difference in specific gravities, tending to orient the plates, is less than the difference for mica in water, while the viscosity opposing the rotation is much greater. As a final argument against orientation by settling, the relation of structures at Mt. Johnson (9) should

be considered. There orientation is vertical and parallel to the sides of a volcanic plug as if dragged upward by eruptions through the channels, while in other respects the structures seem to be identical with those described elsewhere. It therefore seems necessary to adopt the customary view that the orientation of grains here associated with banding is a result of magma movement during crystallization in the general direction of the grains and of the bands, i.e., parallel to the walls of the chamber. This view is so prevalent that the structure is often called "fluxion structure," even when its movement cannot otherwise be determined.

The question remains as to the nature of the movement. The common suggestions are movements of intrusion or of deformation. The writer is in favor of a third suggestion, viz., a circulatory movement. The data on which the argument is based are simple. It will be recalled that the banding of many rocks involves, not only a parallelism of grain, but an alternation—many times repeated—of mineralogically unlike bands. It is also known at Duluth that the extreme differentiates have in a large way become distributed in crudely gravitative positions, i.e., heavy near the bottom and light near the top. With these points in mind the several suggestions may be considered in detail.

Successive intrusions of slightly varying magma are undoubtedly able to produce banded rocks and may even give a crudely gravitative arrangement; but the intrusion of successive layers of alternating composition, a few inches to a few feet thick, until the whole had a thickness of thousands of feet is inconceivable. The process would have to be extremely minute and often repeated in order to explain the detail of some outcrops. But such minute intrusion can hardly account for an intrusion several miles thick, where the intrusive action must have been on a grand scale. Even a process of crystal settling of each intrusive, combined with a sequence of intrusions, does not explain the alternations that are visible in some outcrops, where dozens of alternating bands appear in as many inches.

Turning to heterogeneous intrusion, we find that the idea is accepted without any feeling of shock or surprise when attention is

called to the variety sometimes shown in a series of extrusive lava flows, apparently derived from a single large chamber. The most recent statement of the case is incidental to a discussion of differentiation by crystallization and settling (33). It is necessary to introduce some modification to explain the development of the banded structures often seen. If differentiation took place by settling of crystals, and before the mass was all solid some dynamic process squeezed the liquid out from between the settled crystals, this liquid would not be the same in composition as the supernatant magma. These two liquids might be involved in an intrusive layer and produce bands if not thoroughly mixed before crystallization. There are several difficult points in the application of this idea to such banded rocks as the Duluth gabbro, though it seems clear from the variety of the Keweewanan lava flows that differentiation was well advanced before intrusion.

First, the mechanics of the filter-pressing process in a deep reservoir like a batholith is not stated and is a little hard to conceive. Pressure on a magma is largely hydrostatic and not differential.

Secondly, if heterogeneous liquids were intruded into so large a chamber there would be a great stirring and mixing effect and plenty of time to make the mixture more homogeneous before it crystallized. In general, the larger the mass the more time available for diffusion and mixing. If banding was a result of heterogeneous intrusion, the larger masses would be least banded. As a matter of fact, the Duluth gabbro, one of the largest known intrusions, is most strikingly banded.

Thirdly, there is no reason to assume that the differentiation which caused the variation in the magma in the deep reservoir should suddenly cease upon intrusion into an upper horizon. In fact, from the gravitative arrangement it seems almost certain that some differentiation did take place. To be sure, if the heterogeneous magma varied in specific gravity, the several parts might have been intruded in roughly gravitative position; but even if they were, there was nothing to stop the differentiation until the magma cooled. In so large a mass as the Duluth gabbro there would be plenty of time for further differentiation by settling. The difficulty

arises from the fact that if a crop of crystals settled across the intrusive bands they would destroy the banding and orientation.

Fourthly, the alternation of bands found is so varied and extreme in composition—from anorthosite to peridotite—that the process of filter pressing can hardly yield the liquids which would be needed.

Finally, the alternating bands, if they represent two liquids imperfectly mixed, should consist of a large volume of the upper liquid phase and a smaller amount of the phase strained off or filter-pressed from below. At Duluth there are found small volumes of granophyr and peridotite, with large volumes of anorthosite and immense volumes of olivine gabbro. These would hardly result from filter pressing.

It thus appears that crystal settling and filter pressing and heterogeneous intrusion will not explain the structures at Duluth. However, other modifications of the idea of heterogeneous intrusion may be suggested. The objections mentioned are enough to make them all unsatisfactory. The magmas may come from two reservoirs or become heterogeneous by any other process, but if they did they would have time to mix, and the mixing and crystal settling would destroy the banding. The magmas might be intruded, when partly crystallized, as a great mass with "mushy" consistency. Banding and orientation would be satisfactorily explained by this idea, but in such a banded, mushy mass there would be no opportunity for gravitative differentiation.

It seems necessary to believe that both differentiation and some sort of motion were involved in the production of the bands, and that these occurred after the magma reached its chamber. It may be best to leave the matter open as to the kind of motion that occurred, but the idea of convection is an attractive one.

CONVECTION

It is suggested that many cases of igneous banding are related to convection currents during crystallization differentiation. It is not necessary, in conceiving of this action, to regard it as a very thorough stirring, but rather as some degree of circulation following the intrusion of either homogeneous or heterogeneous magma. Neither is the process exclusive. Successive intrusions of hetero-

geneous material probably occur, and crystal settling, differentiation, and deformation all leave their mark; but these things are apparently not sufficient to produce the structures seen. Convection currents during crystallization result in bands and aid in the differentiation. Such a circulation would drag into parallel position any crystal formed near the wall of the chamber just as it became lodged in the viscous matrix and was removed from circulation. Rhythmic effects in the way of cooling, intrusive action, or gas emanation (all of which are known to be rhythmic) might rhythmically change the mineral composition of the crystals growing along the walls, and thus result in banding. Other features also are favorable and the writer does not find the mechanics of the process at all difficult.

SUMMARY

A review of the descriptions of banding in igneous rocks and a detailed study of the Duluth gabbro show that the alternation of mineralogically unlike bands is commonly accompanied by a fluxion structure and in some places by a sheet jointing.

These structures are found to be parallel to the bounding surfaces of the igneous masses in nearly every case. Exceptions should be carefully studied and the facts in all cases noted, because such a relation of form and structure would be of great value in mapping and economic work.

The banding and related structures probably develop during crystallization, while the magma is in convection circulation.

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